Applied Thermal Engineering 100 (2016) 237–246

Contents lists available at ScienceDirect

Applied Thermal Engineering

journal homepage: www.elsevier.com/locate/apthermeng

Research Paper

Effect of nanofluid concentration and composition on laminar jet impinged cooling of heated steel plate

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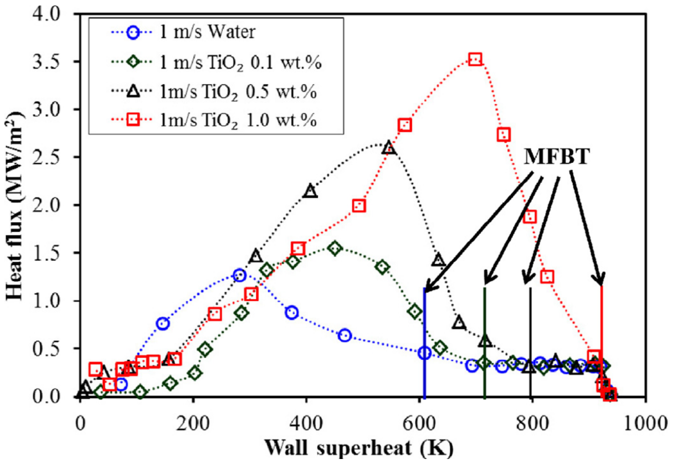
HIGHLIGHTS

- Laminar jet impinged cooling of hot steel plate using TiO_2, Al_2O_3 and SiO_2 nanofluids.
- Effects of concentration, jet velocity and nanoparticle composition studied experimentally.
- Enhancement in heat transfer is obtained using nanofluid jets compared to water.
- Increase in concentration of TiO_2 nanoparticles in nanofluid leads to an increase in CHF.
- Nanofluids with same concentration and different compositions show similar cooling rates.

GRAPHICAL ABSTRACT



ARTICLE INFO

Article history:
Received 27 September 2015
Accepted 10 January 2016
Available online 20 February 2016

Keywords:
Nanofluid
Laminar jet impingement
Nanoparticles
Concentration
Boiling
CHF

ABSTRACT

In this paper, an experimental investigation of heated steel surface cooled by laminar nanofluid jets and its comparison with water jets are presented. The effects of concentration and jet velocity of TiO_2 based nanofluid on cooling rate are evaluated experimentally. Further, the cooling rates of TiO_2, Al_2O_3, and SiO_2 nanofluids with same concentration and velocity are compared. The total heat flux is deduced from the experimentally obtained cooling curves by using a one-dimensional finite volume method based transient inverse heat transfer model. It is found that heat transfer is enhanced using nanofluid jets when compared to water. Increase in concentration of TiO_2 nanoparticle in nanofluid leads to an increase in CHF. Further, it is also observed that the shift from film boiling to transition boiling is faster for nanofluid jet cooled surface.

1. Introduction

Cooling by laminar jet impingement is an attractive process to achieve high rates of heat transfer. Cooling of stationary or moving heated steel surface by impinging laminar jet of sub-cooled water on it has various industrial applications such as Run Out Table (ROT)

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http://dx.doi.org/10.1016/j.applthermaleng.2016.01.032
1359-4311/

cooling, cooling of gas turbine blades and cooling in grinding processes [1]. During rolling operation in steel industry, hot steel strip is rolled continuously and laminar jet of sub-cooled water is impinged on it in order to obtain a predefined cooling rate. The cooling rate is a parameter of great importance resulting in desired microstructure, thereby affecting its mechanical and metallurgical properties. Steel strip has typically a temperature of 1100 K at the beginning of the ROT cooling process and it exits at ~ 500 K. As the exit temperature of the steel strip is beyond the boiling point of water (>373 K) at atmospheric pressure, the heat transfer from the steel strip occurs predominantly due to boiling of water jets. Thus, it is necessary to investigate the boiling heat transfer characteristics of laminar jet impingement on horizontally heated steel strips either stationary or in motion. As the wall superheat is significantly large, all the phases of boiling namely nucleate boiling, transition boiling and film boiling are expected to occur. An extensive research effort is needed to understand the effect of operating parameter on the various aspects of boiling, namely critical heat flux (CHF) and minimum film boiling temperature (MFBT).

Qiu and Liu [2] developed a correlation for CHF for jet impingement of saturated liquids *viz.* water, ethanol, R-11 and R-113 on heated surface and had shown the dependency of CHF on nozzle diameter and jet velocity. Liu and Wang [3] investigated transition and film boiling heat transfer with water jet impinging on a high temperature horizontal flat plate. They found that heat transfer characteristics are strongly affected by the water sub-cooling. The transition boiling occurs for highly sub-cooled water jets and sub-cooling could have a strong effect on the incipient film boiling point. Krishna Kumar et al. [4] developed a model for cooling process on an ROT for hot strip mill and for solution of the model. They examined three numerical models namely, the finite difference method, the orthogonal collocation method, and the integral profile method. Sikdar and Mukhopadhyay [5] described finite difference based model for the analysis of thermal behavior of steel strip during water jet based cooling and determined the heat transfer rate. With the objective to increase heat transfer rate and reduce cooling time, nanofluids may be used in cooling instead of water, as they are known to have higher thermal conductivity and wettability when compared to base fluid and hence, have been a topic of great interest in research [6,7].

Forming of nanofluids requires base fluid such as water with uniformly dispersed nanoparticles of size less than 100 nm. The investigation of nanofluid boiling heat transfer using jet impingement is an emerging area of research. A number of experimental studies [8–14] have been performed to understand the behavior of nanofluids in phase change heat transfer. However, several investigators reported anomalous findings [8–11] on pool boiling regime. The jet impingement boiling heat transfer of water-CuO nanofluid on a large flat plate is experimentally investigated by Liu and Qiu [12]. They reported poor nucleate boiling of nanofluid as compared to water and observed the formation of thin sorption layer of nanoparticles on the surface with an increase of 25% in CHF as compared to water. Chakraborty et al. [13] reported that by using laminar jet of water-TiO_2 nanofluid for cooling of hot steel plate, the cooling rate is significantly enhanced as compared to that of water which leads to changing of microstructure of steel. However, the reason for heat transfer enhancement is not reported in detail. Mitra et al. [14] also investigated boiling heat transfer of nanofluids with concentrations of 0.1 wt.% water-TiO_2 and 0.01 wt.% water-MWCNT jet impingement on a heated steel surface. They reported a significant increase in the cooling rate with nanofluid, whereas no significant change in CHF is observed as compared to that of water. However, the effect of nanofluid composition was not studied by Mitra et al. [14]. Hence, in the present investigation, the effect of various nanofluids and their concentrations on the cooling of heated steel surface using laminar jet impingement is studied. Experiments are performed to obtain cooling curve of heated steel surface, and one dimensional finite volume method based inverse heat transfer model is applied to the measured cooling curve to predict the total heat flux removal rate from the plate surface. A systematic study of total heat flux removal rate by nanofluid is performed along with the comparison of critical heat flux (CHF) and minimum film boiling temperature (MFBT) with water.

2. Theoretical background

In ROT cooling, sub-cooled laminar water jet is impinged on the horizontally moving heated steel strip. In this case, as the temperature of heated surface is significantly higher than the saturation temperature of base fluid, boiling along with radiation are the dominant modes of heat transfer. In pool boiling experiments, different boiling heat transfer zones, such as nucleate, transition and film are reported [15]. However, the fundamental mechanisms of ROT cooling are not yet well understood and characterized. Indeed, well instrumented and sophisticated boiling heat transfer experiments with impinging jet on hot plates in motion are difficult to perform due to technological limitations. Hence, in the present analysis, experiments are performed on stationary steel surface, and pool boiling theory is followed broadly to understand the sequence of events occurring during the cooling process.

Initially as water jet impinges on the hot plate, it is postulated that a thin vapor film is formed due to large wall superheat. During this period, heat transfer predominantly occurs by conduction and radiation as the vapor film prevents direct contact of sub-cooled water to the plate. This region is known as film boiling regime and the radiation heat flux is given by Stefan–Boltzmann law,

$$q''_{rad} = \varepsilon_p \sigma \left(T_s^4 - T_\infty^4\right) \tag{1}$$

In this regime, heat flux removal rate of the order of hundreds of kW/m^2 for surface temperature of the order of 1000 K can be achieved. The vapor film remains stable until the vapor pressure of the film is enough to sustain the pressure of cold water jet over it. As the vapor film breaks, the heat transfer rate increases with decrease in wall superheat till it reaches the maximum heat flux removal rate. This zone of increasing heat flux is known as transition zone as this zone is hydro-dynamically unstable marked with an increase in contact area of sub-cooled water with hot plate as wall superheat decreases. The maximum heat removal rate is called critical heat flux (CHF). Beyond CHF, third zone known as nucleate boiling regime starts, where sub-cooled water comes in complete contact with hot plate. Heat transfer in this zone occurs due to continuous nucleation of small bubbles and the heat flux removal rate gradually decreases with decreasing wall superheat.

For laminar jet cooling, the typical experimental value of CHF and the corresponding wall superheat are higher than that of typical pool boiling heat transfer [16] with a dependence on the jet velocity [3]. This may be due to the fact that the jet cooling is governed by the forced convection of the sub-cooled liquid and is unsteady in nature [14], while typical pool boiling is governed by the natural convection and is quasi static in nature.

3. Experimental setup

The schematic diagram of experimental setup is shown in Fig. 1. Major components of the setup are heated steel plate with K-type thermocouples (TC) embedded, centrifugal pump, two tanks (storage and collection tank), refractory brick, data acquisition system, and digital flow meter. A nozzle with an inner diameter (d) of 5 mm and length of 20 mm is used to discharge the laminar jet of coolants, water, and nanofluids. Temperature of the cooling fluid used in the experiment is 30 °C. Laminar jet falls on the heated horizontal steel